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EVIDENCE AGAINST A CONSTANT-DIFFERENCE EFFECT IN CONCURRENT-CHAINS SCHEDULES

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Savastano and Fantino (1996) reported that in concurrent-chains schedules, initial-link choice proportions remained constant as terminal-link durations increased as long as the subtractive difference between the two terminal-link schedules remained constant. Two experiments with pigeons were conducted to examine this constant-difference effect. Both experiments used equal variable-interval schedules as initial links. The terminal links were fixed delays to reinforcement in Experiment 1 and variable delays to reinforcement in Experiment 2. The durations of the terminal links were varied across conditions, but the difference between pairs of terminal links was always 10 s. In both experiments, preference for the shorter terminal link became less extreme as terminal-link durations increased, so a constant-difference effect was not found. It is argued, however, that this choice situation does not provide clear evidence for or against delay-reduction theory versus other theories of choice.

Key words: concurrent-chains schedules, delay-reduction theory, fixed delays, variable delays, key peck, pigeons

One of the most common procedures used in research on choice behavior is the concurrent-chains schedule. In a typical concurrent-chains schedule, two identical variable-interval (VI) schedules are used as initial links, and completion of either VI schedule leads to its terminal link—another reinforcement schedule that leads to food. Relative response rates in the initial-link schedules (expressed either as a ratio of the two response rates or as the proportion of responses made on one schedule) are used as measures of the subject's preference for the terminal links.

In two experiments with pigeons, Savastano and Fantino (1996) found that initial-link response ratios on concurrent-chains schedules remained constant as long as the subtractive difference between the lengths of the two terminal-link schedules remained constant. Their initial links were identical VI 60-s schedules, and their terminal links were pairs of VI schedules that always differed by a mean of 20 s. For example, in one condition the two terminal links were VI 5 s and VI 25 s, and in another condition the two terminal links were VI 100 s and VI 120 s. Savastano and Fantino found no systematic changes in preference as long as the difference between the two terminal links was kept constant at 20 s. More recently, Fantino and Goldshmidt (2000) obtained similar results in a series of experiments with pigeons that used a very different procedure—a foraging analogue called the successive-encounters procedure.

Savastano and Fantino (1996) showed that this finding, the *constant-difference effect,* was inconsistent with several different mathematical models of choice, including melioration theory (Vaughan, 1985), incentive theory (Killeen & Fantino, 1990), and Davison's (1988) extension of the hyperbolic decay model. Each of these models predicts that preference for the shorter terminal-link schedule should decrease toward indifference as the durations of the terminal-link schedules become longer. The constant-difference effect is also counterintuitive, because it contradicts Weber's law about the discriminability of stimuli: The difference between VI 100 s and VI 120 s should be harder to discriminate than the difference between VI 5 s and VI 25 s, and therefore one might expect less extreme preference with the longer pair of schedules.

Although the constant-difference effect may be counterintuitive, Savastano and Fantino (1996) showed that it is predicted by Fantino's (1969) delay-reduction theory. In its simplest form, delay-reduction theory can be expressed as follows:

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$$\frac{B_L}{B_R} = \frac{T - t_L}{T - t_R}, \qquad (1)$$

where B_L and B_R are responses in the left and right initial links, T is the average time between food reinforcers, and t_L and t_R are the mean durations of the left and right terminal links. In essence, delay-reduction theory states that preference for a terminal link depends on the amount of delay reduction that occurs when a terminal link is entered. For the condition with VI 5-s and VI 25-s terminal links described above, $T = 45$ s (because the average durations of the initial and terminal links are 30 s and 15 s, respectively). Therefore, according to Equation 1, $B_L/B_R = (45 - 5)/(45 - 25) = 2$. For the condition with VI 100-s and VI 120-s terminal links, $T = 140$ s, so $B_L/B_R = (140 - 100)/(140 - 120) = 2$. Thus for both of these conditions (and for all others with a 20-s difference between the terminal links), Equation 1 predicts a 2:1 preference for the shorter terminal link.

To accommodate cases with unequal initial-link schedules, Squires and Fantino (1971) proposed the following modification of Equation 1, which has been used in much of the subsequent research on delay-reduction theory:

$$\frac{B_L}{B_R} = \frac{r_L(T - t_L)}{r_R(T - t_R)}, \qquad (2)$$

where r_L and r_R are the overall rates of food delivery for the left and right alternatives. Savastano and Fantino (1996) noted that Equation 2 predicts a slight decline in preference with increasing terminal-link durations, but the predicted decline is so small that they considered it to be insignificant. Therefore, both versions of delay-reduction theory predict little or no change in preference as long as the subtractive difference between the two terminal links remains constant.

Because the constant-difference effect is a surprising result, and because it is inconsistent with the predictions of several different models of choice, the present experiments were conducted to collect additional data on this phenomenon, using procedures that differed in several ways from those of Savastano and Fantino (1996). As in the experiments of Savastano and Fantino, the present experiments used equal VI schedules as the initial links. However, whereas Savastano and Fantino used VI schedules as terminal links, in the present experiments the terminal links were delays followed by food. In Experiment 1, the terminal links were fixed-time (FT) schedules (in which food was delivered after a fixed delay, with no response required). In Experiment 2, the terminal links were variable-time (VT) schedules (in which food was delivered after a variable delay, with no response required). In both experiments, the durations of the terminal links were varied across conditions, but there was always a 10-s difference between the mean durations of the two terminal links. Notice that there is nothing in Equation 1 or Equation 2 that restricts the constant-difference effect to a particular type of terminal-link schedule. In addition, unlike VI terminal links, which require a response for the delivery of the reinforcer, FT and VT schedules allow precise control of the terminal-link durations. This ensures that the differences between terminal links are precisely the same in all conditions. Therefore, the present experiments were conducted to determine whether a constant-difference effect would be obtained with FT and VT terminal-link schedules.

EXPERIMENT 1

Method

Subjects. The subjects were 8 White Carneau pigeons maintained at about 80% of their free-feeding weights. All had previous experience with a variety of experimental procedures.

Apparatus. Two experimental chambers, each 30 cm long, 30 cm wide, and 33 cm high, were used. Both chambers had three response keys, each 2 cm in diameter, mounted in the front wall of the chamber, 24 cm above the floor and 7 cm apart, center to center. The center key was not used in this experiment. A force of approximately 0.15 N was required to operate each key. Each key could be transilluminated with lights of different colors. A hopper below the center key provided controlled access to grain, and when grain was available, the hopper was illuminated with a 2-W white light. Pairs of 2-W lights were mounted above the Plexiglas ceiling of each chamber (white, orange, and blue lights in one chamber, and white, red,

Table 1

Terminal-link durations (in seconds) and mean percentages of left-key responses in Experiment 1.

Condi-	Terminal link		Bird							
tion	Left	Right	1	2	3	4	5	6	7	8
1	2	12	95.1	69.6	84.7	83.1	77.4	65.3	79.0	76.3
2	50	40	13.7	32.1	29.8	54.0	21.0	50.5	54.3	33.2
3	12	2	33.3	37.0	8.6	38.6	13.2	27.5	28.8	24.0
4	40	50	52.4	80.8	59.5	81.8	57.2	36.4	49.1	39.9
5	50	40	29.9	35.4	38.0	60.5	5.1	34.2	41.1	23.9
6	2	12	92.7	62.3	80.1	88.1	82.1	66.5	83.0	73.9
7	40	50	60.9	71.4	83.2	84.2	67.8	47.1	70.9	34.5
8	12	2	24.6	41.9	19.9	31.8	10.1	22.4	14.4	12.0
9	90	100	54.7	73.0	68.8	67.4	26.5	43.5	48.6	44.4
10	100	90	49.8	64.7	82.4	71.3	10.9	47.4	39.7	58.3

and green lights in the other). Each chamber was enclosed in a sound-attenuating box containing a ventilation fan. All stimuli were controlled and responses recorded by an IBM®-compatible personal computer using the Medstate® programming language.

Procedure. Birds 1 through 4 were tested in one chamber, which had orange and blue keylights and houselights. Birds 5 through 8 were tested in the other chamber, which had green and red keylights and houselights. The description of the procedure below applies to the first chamber; the procedure in the second chamber was the same except for the difference in key and houselight colors.

Experimental sessions were usually conducted 6 days per week. Throughout the experiment, a concurrent-chains procedure was used, in which a single VI 30-s schedule operated in the initial links and each terminal link was an FT schedule that consisted of a fixed delay followed by a 3-s food presentation. In the initial links, the white houselights were lit and the two side keys were illuminated, the left key orange and the right key blue. The VI 30-s schedule assigned terminal links to the two response keys with equal probability, using a pseudorandom sequence that ensured that the actual percentage of terminal links for each key was close to 50%. Once a terminal link was assigned to one key, the VI timer stopped and did not restart until that terminal link was entered and completed. When a terminal-link entry was assigned to a key, the next peck on that key extinguished all keylights and the terminal link began.

The terminal link for the left key was a fixed delay with the orange houselights on, and the terminal link for the right key was a fixed delay with the blue houselights on. Each terminal link ended with a 3-s presentation of grain, and only the white light above the grain was lit during the reinforcement period. After each food presentation, the keylights and white houselights were again illuminated, and the next initial link began. Each session ended after 60 min or 80 reinforcers, whichever came first.

The experiment consisted of 10 conditions. In different conditions, the pairs of terminal-link durations were 2 s and 12 s, 40 s and 50 s, or 90 s and 100 s. The left columns of Table 1 show the terminal-link durations in each condition. Each condition lasted for a minimum of 20 sessions. For each session, the percentage of initial-link responses on the left key was calculated. After 20 sessions, a condition was terminated for each subject individually when the following stability criteria were met: (a) Neither the highest nor the lowest single-session response percentage could occur in the last six sessions of a condition. (b) The mean response percentage across the last six sessions could not be the highest or the lowest six-session mean of the condition. (c) The mean response percentage of the last six sessions could not differ from the mean of the preceding six sessions by more than 5%.

Results and Discussion

The number of sessions required to meet the stability criteria ranged from 20 to 46 (median = 25 sessions). The results from the

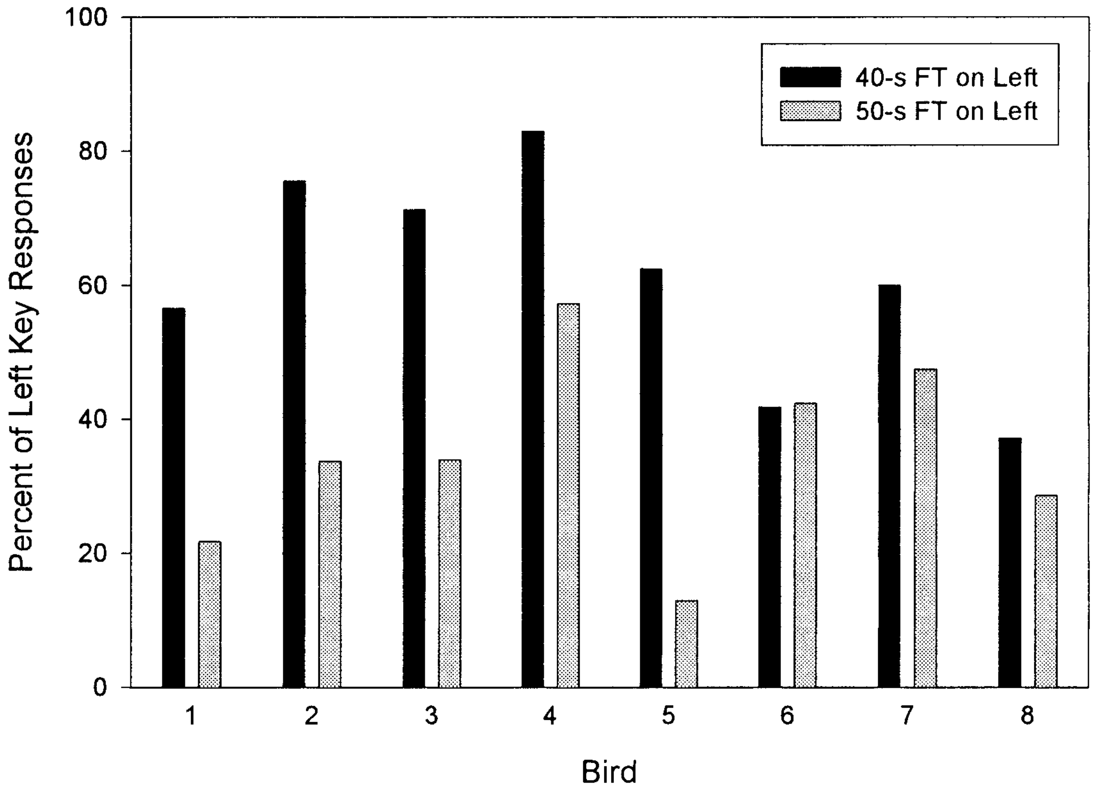

Fig. 1. For each bird in Experiment 1, the percentage of left-key responses is shown for conditions with the FT 40-s schedule on the left and for conditions with the FT 50-s schedule on the left. Each bar is the mean of two determinations.

six sessions that satisfied the stability criteria were used in all data analyses.

For each subject, Table 1 shows the mean percentage of left-key responses in each of the 10 conditions. To provide the most convincing evidence against a constant-difference effect, the results should show (a) that the pigeons' responses were under appropriate schedule control (i.e., that they were able to discriminate the difference between a given pair of terminal links) and (b) that response percentages shifted closer to indifference with longer terminal links. The results from the conditions with terminal links of 90 s and 100 s (Conditions 9 and 10) did not meet the first criterion. Four of the 8 birds had a higher left-key response percentage when the 90-s schedule was on the left, but the other 4 showed an increase in the left-key response percentage when the 100-s schedule was switched to the left in Condition 10. Averaged across birds, the left-key response percentage was 53.4% in Condition 9 and 53.1% in Condition 10. These results provide no evidence that the birds could discriminate between the 90-s and 100-s terminal links, so the data from these two conditions will not be considered further.

However, the results indicate that the birds could discriminate between the 40-s and 50-s terminal links. Figure 1 shows the mean left-key response percentages from the conditions with the 40-s terminal link on the left and with the 50-s terminal link on the left. The results are averaged across replications. For 7 of the 8 pigeons, the percentages were higher when the 40-s terminal link was on the left. Averaged across birds, the response percentages were 61.0% with the 40-s terminal link on the left and 34.8% with the 50-s terminal link on the left, and the difference between these conditions was statistically significant, $t(7) = 4.19$, $p < .01$. Further evidence for discrimination between the 40-s and 50-s terminal links can be seen in the sequences of reversals shown in Table 1. A comparison

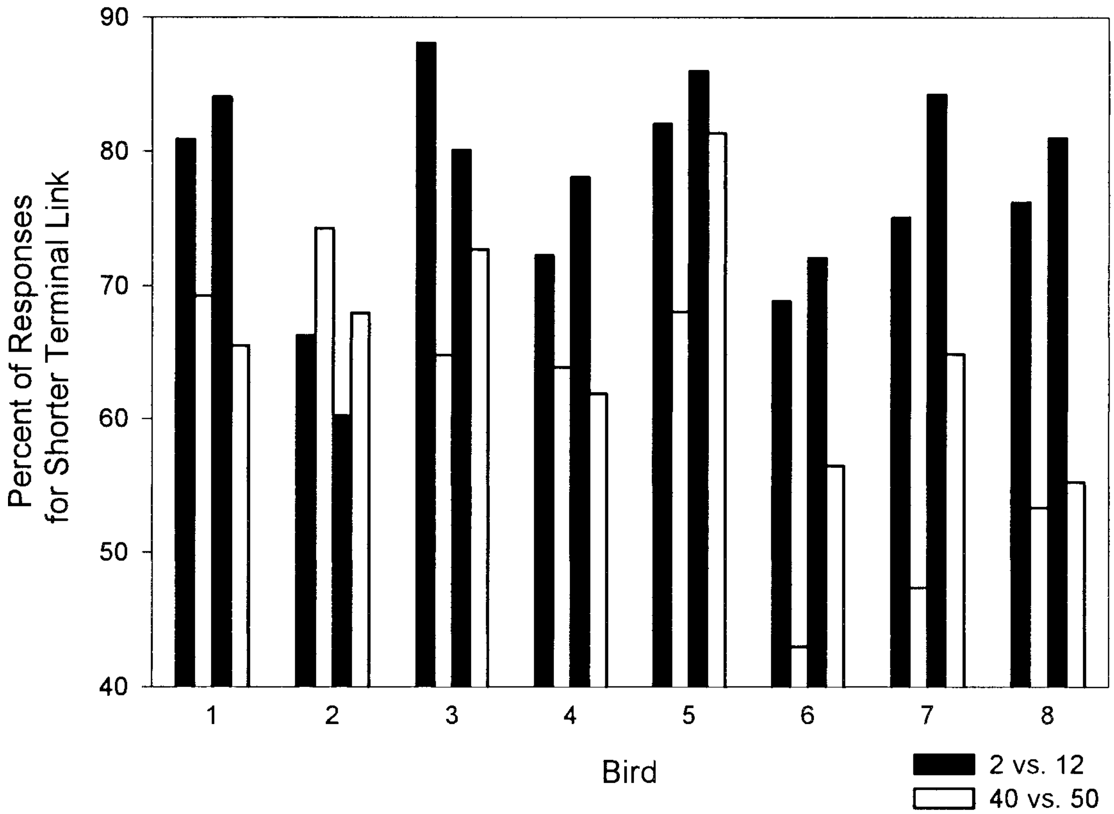

Fig. 2. For each bird in Experiment 1, the percentage of responses on the key with the shorter terminal link is shown. The first two bars are from Conditions 1 through 4, and the last two bars are from Conditions 5 through 8. Each bar is the average of two conditions in which the left and right positions of the terminal links were reversed.

of Conditions 2 and 4 shows that the response percentages increased for 6 of the 8 pigeons when the FT 40-s schedule was switched to the left key. The response percentages then decreased for all 8 birds when the FT 40-s schedule was switched back to the right key in Condition 5. When the FT 40-s schedule was again on the left in Condition 7, response percentages were higher than in Condition 5 for all 8 birds.

To test the constant-difference effect, response percentages on the key with the shorter terminal link from the conditions with 2-s and 12-s terminal links were compared to those from the conditions with 40-s and 50-s terminal links. Figure 2 shows that, for 7 of the 8 pigeons, response percentages were lower in the conditions with 40-s and 50-s terminal links than in the conditions with 2-s and 12-s terminal links. The average response percentage was 77.2% in the conditions with 2-s and 12-s terminal links and 63.2% in the conditions with 40-s and 50-s terminal links. A two-way repeated measures analysis of variance (ANOVA) found a significant effect of terminal-link duration, $F(1, 7) = 14.85$, $p < .01$, no significant effect of replication, $F(1, 7) = 2.70$, and no Duration × Replication interaction, $F(1, 7) = 1.06$. These results, therefore, provide evidence against a constant-difference effect.

There were several procedural differences between this experiment and the studies of Savastano and Fantino (1996), any of which might have led to a difference in results. One obvious difference is that this experiment used FT schedules as terminal links, whereas Savastano and Fantino used VI schedules. At the very least, the results of Experiment 1 suggest that a constant-difference effect is not a universal result with concurrent-chains schedules, because the effect was not obtained with FT terminal links. To examine the possibility that a constant-difference effect

Table 2

Terminal-link durations (in seconds) and mean percentages of left-key responses in Experiment 2.

Condition	Terminal link		Bird			
	Left	Right	1	2	3	4
1	12	2	40.4	41.3	38.5	41.0
2	50	40	82.6	48.3	60.8	52.9
3	40	50	83.4	59.2	68.8	60.8
4	2	12	86.3	63.1	72.0	66.0
5	12	2	74.9	48.1	30.6	43.5
6	2	12	90.3	64.3	63.5	68.5

might be found with variable rather than fixed terminal-link schedules, Experiment 2 used VT schedules in place of the FT schedules. Except for this change, the procedures were the same as those of Experiment 1.

EXPERIMENT 2

Method

Subjects and apparatus. Birds 1 through 4 from Experiment 1 served as the subjects, and they were tested in the same experimental chamber.

Procedure. The procedure was the same as in Experiment 1, with orange and blue keylights and houselights signaling the initial and terminal links, but the terminal links were VT schedules rather than FT schedules. Each VT schedule was composed of 15 different delays selected to approximate an exponential distribution, following the progression described by Fleshler and Hoffman (1962). In different conditions, the mean terminal-link delays were either 2 s and 12 s or 40 s and 50 s. The experiment included six conditions, as shown in Table 2. As in Experiment 1, each condition lasted for a minimum of 20 sessions, and the same stability criteria were used to terminate a condition.

Results and Discussion

The number of sessions required to meet the stability criteria ranged from 20 to 29 (median = 20 sessions). The results from the six sessions that satisfied the stability criteria were used in all data analyses. For each bird, Table 2 shows the mean percentage of left-key responses in each of the six conditions.

As with Experiment 1, the results were analyzed in two steps. First, the results from Conditions 2 and 3 were compared, to determine whether the pigeons could discriminate between the 40-s and 50-s VT schedules. Table 2 shows that left-key response percentages were slightly higher for all 4 birds when the 40-s VT schedule was on the left. Although the left-key response percentage was above 50% for 3 of the 4 birds in Condition 2, the difference between Conditions 2 and 3 was statistically significant, $t(3) = 3.21$, $p < .05$. Table 2 also shows, however, that left-key response percentages were very high for Bird 1 in all conditions except Condition 1, possibly indicating a strong left-key bias. If the results from Bird 1 are excluded, the response percentages from Conditions 2 and 3 are still statistically significant, $t(2) = 8.99$, $p < .02$.

To test the constant-difference effect, response percentages on the key with the shorter terminal link from the conditions with 2-s and 12-s terminal links were compared to those from the conditions with 40-s and 50-s terminal links. These response percentages are shown in Figure 3, in which each bar is the mean of two conditions in which the location of the shorter VT schedule was reversed. The average response percentage for the key with the shorter terminal link was 63.5% in the conditions with 2-s and 12-s terminal links and 53.5% in the conditions with 40-s and 50-s terminal links. A repeated measures ANOVA found a significant effect of terminal-link duration, $F(2, 6) = 7.53$, $p < .05$. If the results from the bird with a strong position bias (Bird 1) are excluded from the analysis, the effect of terminal-link duration is still significant, $F(2, 4) = 10.51$, $p < .05$. Therefore, as with the FT terminal links used in Experiment 1, these results with VT terminal links also provide evidence against a constant-difference effect.

GENERAL DISCUSSION

These experiments found that preference for the shorter terminal link decreased as the durations of the terminal links were increased while the subtractive difference between the two links was kept constant at 10 s. The decrease in preference toward indifference with longer terminal links was found with both fixed delays (Experiment 1) and variable delays (Experiment 2). These studies, therefore, do not support the constant-

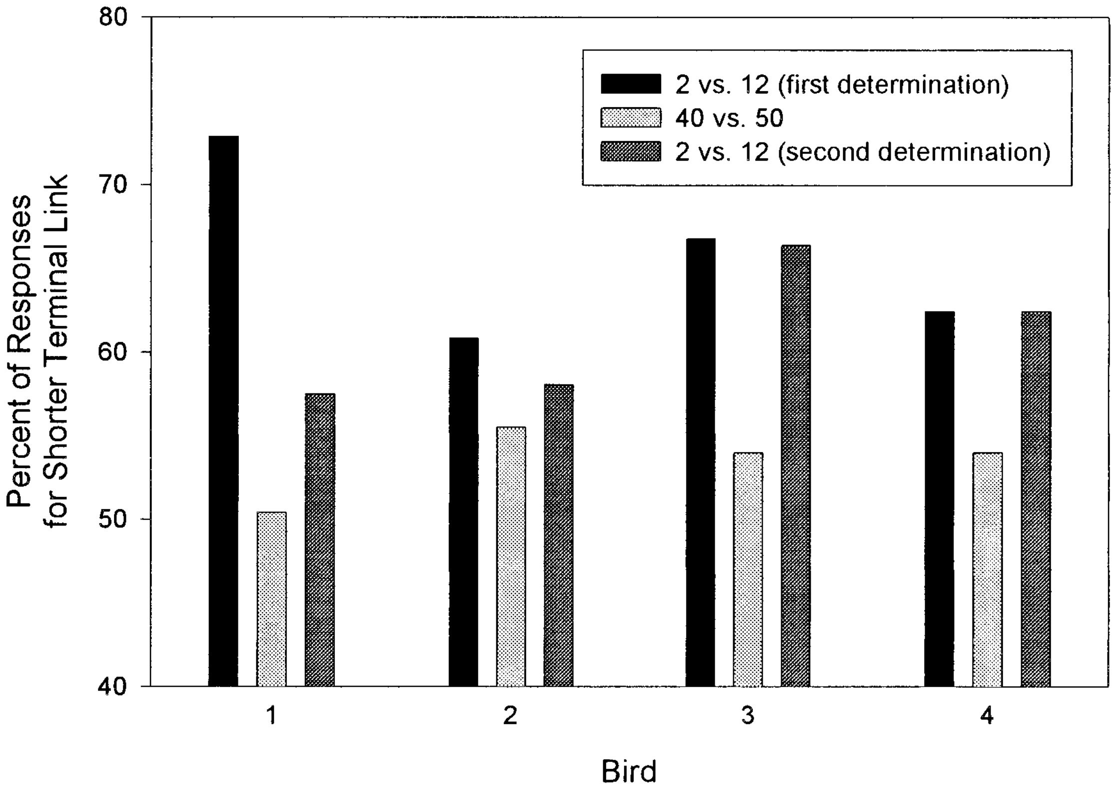

Fig. 3. For each bird in Experiment 2, the percentage of responses on the key with the shorter terminal link is shown. Each bar is the average of two conditions in which the left and right positions of the terminal links were reversed.

difference effect predicted by delay-reduction theory (Equation 1). The decreased preference with the 40-s and 50-s terminal links cannot be attributed to a failure to discriminate the difference between these two schedules, because in both experiments there were statistically significant changes in preference when the positions of the two schedules were reversed across conditions.

It is not clear why these results differed from those of Savastano and Fantino (1996), but several points can be made. In their first experiment, Savastano and Fantino found indications of both position bias and order effects, and as a result, the data points from individual subjects were variable. It is possible that this variability obscured any trend toward indifference that might have been present in the data. Their second experiment, however, controlled for position bias by randomly alternating the positions of the two schedules after each reinforcer. In that experiment, some of the birds showed slightly less extreme choice percentages with longer terminal links, but averaged across all birds, the decrease in preference was only about 1%. In comparison, the average decreases in preference between the 2-s versus 12-s schedules and the 40-s versus 50-s schedules in the present two experiments were 14% and 10%, respectively.

One procedural difference between the studies is that Savastano and Fantino (1996) used VI schedules as terminal links, whereas FT and VT schedules were used in the present experiments. Although the difference in results between these studies could be due to the use of response-independent rather than response-dependent terminal links, this possibility seems unlikely. Other experiments that used schedules of response-independent food delivery as terminal links have found results similar to those from studies with response-dependent terminal-link schedules. For example, preference for the shorter of two FT terminal links increases if the durations of both are increased by the same multiplier (Omino, 1993), just as with FI and VI schedules (MacEwen, 1972). Animals prefer VT terminal links over FT terminal links of the same mean duration (Rider, 1983), just as they prefer VI over FI terminal links (Herrnstein, 1964). Davison, Alsop, and Denison (1988) found no systematic preferences between FI terminal links and equally long FT terminal links. These results, and others, suggest that terminal links with response-dependent and response-independent food delivery have similar effects on choice.

To what extent does evidence for or against the constant-difference effect help to distinguish among different theories of concurrent-chains performance? As Savastano and Fantino (1996) demonstrated, several different mathematical models predict that a constant-difference effect should not occur, and that preference should decline toward indifference with longer terminal links (e.g., Davison, 1983, 1988; Killeen & Fantino, 1990; Vaughan, 1985). A model that I have recently developed, the hyperbolic value-added model (Mazur, 2001), also predicts such a decline toward indifference. The data from the present experiments are therefore consistent, at a qualitative level, with all of these models, whereas the results of Savastano and Fantino are not.

On the surface, the results of the present experiments appear to pose problems for both delay-reduction theory (Fantino, 1969) and Grace's (1994) contextual choice model. The simplest version of delay-reduction theory (Equation 1) predicts a strict constant-difference effect. Savastano and Fantino (1996) also showed that the contextual choice model predicts relatively little change in preference across a wide range of terminal-link values (although it does predict a very sharp increase in preference with very short terminal links). However, the evidence against a constant-difference effect is not as damaging to these theories as it might appear, for several reasons.

First, the most widely used version of delay-reduction theory (Equation 2) does predict a slight decline toward indifference with longer terminal links, because the ratio of the two reinforcement rates (r_L and r_R) becomes less extreme. Similarly, the contextual choice model also predicts a slight decline in preference with longer terminal links. Although the decreases in choice percentages predicted by these two models are quite small if no free parameters are used, the predicted decreases can be amplified if free parameters are added to the models. Grace (1994, 1996) used several free parameters when applying the contextual choice model to data sets from published studies on concurrent-chains schedules. Delay-reduction theory can also make good quantitative predictions for these same data sets, but only if free parameters, comparable to those used by Grace, are added to Equation 2 (Mazur, 2001). Once free parameters are included, the predictions of delay-reduction theory, the contextual choice model, and other theories about the constant-difference effect become harder to distinguish.

In summary, contrary to the findings of Savastano and Fantino (1996), the present experiments found evidence against a constant-difference effect in concurrent-chains schedules. However, the presence or absence of a constant-difference effect does not provide strong evidence for or against different models of choice. All of the models discussed (except the simplified version of delay-reduction theory described by Equation 1) predict at least a slight decline in preference with longer terminal links. The models differ only in their predictions about the amount and rate of the decrease in preference, and these predictions can be modulated through the use of free parameters. There are ways to conduct tests that can clearly distinguish among the predictions of different models of concurrent-chains choice (see Mazur, 2000, 2001), but examining the validity of the constant-difference effect may not provide a critical test of competing models.

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